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PICKERING SEISMIC SAFETY MARGIN - METHODOLOGY

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by

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Research report

PICKERING SEISMIC SAFETY MARGIN — METHODOLOGY

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ABSTRACT

A study was conducted to recommend a methodology for the seismic safety margin review of existing Canadian CANDU nuclear generating stations such as Pickering A. The purpose of the seismic safety margin review is to determine whether the nuclear plant has sufficient seismic safety margin over its design basis to assure plant safety. In this review process, it is possible to identify the weak links which might limit the seismic performance of critical structures, systems and components. The proposed methodology is a modification the EPRI (Electric Power Research Institute) approach. The methodology includes: the characterization of the site margin earthquake, the definition of the performance criteria for the elements of a success path, and the determination of the seismic withstand capacity. It is proposed that the margin earthquake be established on the basis of using historical records and the regional seismo-tectonic and site specific evaluations. The ability of the components and systems to withstand the margin earthquake is determined by database comparisons, inspection, analysis or testing. An implementation plan for the application of the methodology to the Pickering A NGS is prepared.

RÉSUMÉ

Le présent rapport traite d'une méthodologie proposée pour examiner la marge de sécurité des centrales nucléaires canadiennes CANDU, comme la centrale Pickering A, en cas de séisme. L'examen vise à déterminer si la marge de sécurité supplémentaire de la centrale est suffisante par rapport à l'hypothèse de base et à déceler les faiblesses qui pourraient limiter la capacité des structures, des systèmes et des composants fondamentaux de résister à un séisme. La méthodologie proposée est une modification de l'approche du Electric Power Reseach Institute (EPRI) et comprend les éléments suivants : la formulation des caractéristiques du site pour résister à un tremblement de terre, la définition des critères de rendement pour les éléments du cheminement critique et l'établissement de la capacité de résister à un séisme. Les auteurs proposent d'établir le séisme auquel les systèmes de sûreté peuvent résister à l'aide de dossiers historiques et d'évaluations sismotectoniques régionales et de site spécifiques. La capacité des composants et des systèmes de résister à un séisme peut être établie grâce à des comparaisons de bases de données, à des inspections, à des analyses ou à des épreuves. Le rapport propose aussi un plan d'application de la méthodologie à la centrale nucléaire Pickering A.

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PICKERING SEISMIC SAFETY MARGIN - METHODOLOGY

EXECUTIVE SUMMARY

It has been generally accepted that it is possible that an existing Nuclear Power Plant (NPP) could be subjected to a level of earthquake greater than that for which it was designed. In addition, some existing power plants were designed before the development of CSA N289 seismic design codes. Methodologies have been developed in several countries to demonstrate the ability of NPPs to withstand earthquakes beyond their design basis.

The objective of this study is to recommend a methodology for assessing the seismic withstand capacity of existing CANDU NPPs such as Pickering A NGS. The purpose of the methodology is to provide the procedure to determine what is the seismic safety margin that the NPP has over its design basis to ensure plant safety. In the process, it is also possible to identify the weak links which might limit the seismic performance of any particular critical structures, systems and components. The study is intended to prepare an implementation plan for the application of the methodology for an existing plant. The most important conclusions and recommendations of the study are:

a) The EPRI margin approach is judged to be the most suitable for such review.

b) The recommended methodology is an adaptation of the EPRI approach to suit the particular CANDU conditions at an eastern Canadian location and involves the following steps:

- selection of the review team
- determination of the margin earthquake
- definition of the performance criteria
- determination of the preferred success path and alternate path(s)
- prescreening by evaluations and field inspection
- seismic margin review work
- documentation.

c) A methodology is proposed for the determination of the margin earthquake on the basis of seismo-tectonic, regional and local site considerations.

d) A success path for the NPP includes structures, systems and components involved in the sequence of operational procedures for:
   - safe shutdown of the reactor and maintenance of the shutdown condition
   - decay heat removal from the fuel
   - containment of postulated radioactive releases
   - monitoring and control of critical and safety functions

e) The risk of consequential events, emergency measures for staff and the public, the risk of loss of function due to nonseismic causes and human performance are important aspects of the margin review.

PICKERING SEISMIC SAFETY MARGIN - METHODOLOGY

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LIST OF ACRONYMS AND SYMBOLS

AECB	Atomic Energy Control Board
APE	Annual Probability of Exceedance
BWR	Boiling water reactor
B&PV	Boiler and Pressure Vessel Code
CDFM	Conservative deterministic failure margin
CSA	Canadian Standards Association
DBE	Design basis earthquake
DSMA	Deterministic seismic margin assessment
ECIS	Emergency Cooling Injection System
EPRI	Electric Power Research Institute
EPS	Emergency power supply
ERS	Experience response spectra
GERS	Generic equipment ruggedness spectrum
GRS	Ground response spectrum
$GRS_{1,2}$	Ground response spectra 1 or 2
HCLPF	High-confidence-of-low-probability of failure
HVAC	Heating, ventilation and air conditioning
Hz	Hertz (cycles per second)
IPEEE	Individual plant examination of external events
II/I	Non-seismic category II components over seismic category I components
LOCA	Loss of coolant accident
M	Magnitude of earthquake
MCE	Maximum credible earthquake
ME	Margin earthquake
NBCC	National Building Code of Canada
NC	Nuclear class
NEP	Non-exceedance probability
NGS	Nuclear generating station
NOL	Normal operating load
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
OBE	Operating basis earthquake
PGA	Peak ground acceleration
PRA	Probabilistic risk assessment
PWR	Pressurized water reactor

R	Epicentral distance
$Sa_{1,2}$	Spectral ordinates 1 or 2
SDE	Site design earthquake
SI	Seismic spatial system interaction
SMA	Seismic margin assessment
SME	Seismic margin earthquake
SMR	Seismic margin review
SPLD	Success path logic diagram
SPRA	Seismic probabilistic risk assessment
SRT	Seismic review team
SSE	Safe shutdown earthquake
SSMRP	Seismic safety margin research program
TRS	Test response spectrum
UBC	Uniform Building Code
UHS	Uniform hazard spectrum
US	United States
USNRC	Unites States Nuclear Regulatory Commission
f_o	Frequency of free vibration
g	Gravitational constant (9.81 m/s)
kPa	Kilo pascal

1. INTRODUCTION

It is the mission of the regulatory body, the Atomic Energy Control Board (AECB), to ensure that radiological risks resulting from the effects of earthquakes on nuclear facilities do not exceed acceptable levels. No numerical criteria exist in the Canadian licensing regulations, but it can be inferred that the frequency of an unacceptable postulated release must be kept below 10^{-6} per annum. However, seismic events are not well defined to produce these low frequency levels in eastern Canada, where Canadian nuclear power generating stations are located. The design earthquakes have been chosen at about the 10^{-3} frequency level, a level commensurate with the limits of regional statistical data.

At the time that a nuclear power plant (NPP) is committed to design, the best available knowledge is used to set the design basis earthquake (DBE). The DBE is an engineering representation of the potentially severe ground motion at the site that has a low probability of being exceeded during the lifetime of the plant. The process of design, testing, fabrication and construction is continuously being monitored and improved.

Recent work and experience in Canada and the US suggests that the perception of seismic hazard for nuclear power plant sites in eastern Canada may change as a result of new knowledge and information. Consequently, it is possible, although unlikely, that an existing nuclear power plant may be subjected to a level of earthquake ground motion greater than that for which it was designed. On the other hand, experience from real earthquakes suggests that modern structures and equipment may well be able to withstand ground motions substantially greater than their design basis earthquake level.

The Pickering A NGS is the oldest operating plant in Canada. It was selected for this study because the "A" station was designed to seismic standards that are different from what is currently specified by codes for modern plant design.

Given the current situation with the Pickering A station, several important questions arise:

a) What is the largest earthquake that is credible to occur at or near the site (maximum credible earthquake, MCE)?
b) What is the largest earthquake that the Nuclear Power Plant (NPP) can be subjected to without compromise of safety and containment of the radioactive material (margin earthquake, ME)?
c) If the largest earthquake that the plant can safely sustain is less than the largest credible earthquake expected at the site, what is the most economical plant modification to upgrade its capacity to withstand earthquakes?

These questions are complex and difficult to answer. The determination of the largest earthquake that is credible at the site is constrained by the available seismo-tectonic information and the short history of recorded earthquakes. The confidence in events with very low probability of occurrence is fairly limited. The question concerning the largest earthquake that the Pickering A plant can safely sustain is an open-ended question and is difficult to answer due to the complex nature of a Nuclear Generating Station. In practical terms, the answers to the first and second questions, if pursued, would involve such large uncertainties as to be unusable. However, a more useful approach to seismic safety of such a plant is to ask questions such as: given an earthquake, can the nuclear power plant safely survive the postulated seismic event? What are the minimum required modifications to enable the plant to carry out its safety functions such as the safe shutdown of the reactor and the containment of radioactivity, if the plant cannot survive such an event? From an engineering point of view, these are much easier questions to answer.

Methodologies have been developed in the US by the United States Nuclear Regulatory Commission (USNRC) and the Electric Power Research Institute (EPRI) for demonstrating the ability of a nuclear power plant to withstand a given earthquake beyond the design basis. These studies were used to create a methodology for the review of Canadian nuclear power plants to withstand a given earthquake beyond the design basis level. In particular, such a review is important to those plants that were designed before the CSA N289 seismic design code came into use in 1980. The concept of margin earthquake (ME) was used in formulating the margin review methodology. The ME has been applied by a number of countries to serve as a regulatory seismic margin assessment earthquake to bridge the gap between the frequency of the design

basis earthquake and the much lower frequency of the unacceptable radiation release event.

In this study, a methodology for the review of the seismic safety margin of CANDU NPPs such as Pickering A Nuclear Generating Station (NGS), is recommended. The purpose of the methodology is to create the framework and procedure to determine what is the seismic safety margin that the NPP has over its design basis to ensure plant safety. As a supplementary benefit, weak links which might limit the seismic performance of critical structures, systems and components would be identified.

This report contains 5 chapters. The first two chapters introduce the subject of the study and identify the objectives of the work. The seismic margin review methodology that best suits the Pickering A NGS conditions is recommended in Chapter 3. The rationale for the recommended procedure is reviewed. The variations of the proposed approach from the available methodologies are summarized.

The plan for implementing the seismic margin review at the Pickering A NGS is outlined in Chapter 4. The implementation plan includes the selection of the review team, the determination of the margin earthquake, and the description of the technical basis for the review. The process for identifying systems and elements in a success path is described. The satisfactory performance of the structures and components within this success path when the plant is subjected to the ground motion of the margin earthquake is expected to ensure 1) the safe shutdown of the reactor, 2) continuing the cooling of the fuel, 3) the containment of postulated radioactive releases and 4) the continued monitoring of critical systems and functions. Field inspection and surveys for the purposes of determining the preferred success path and alternate path(s) and the screening of plant components are discussed. The evaluation of the seismic margin of various components is conducted against design and performance criteria. The documentation required for the seismic margin review study is summarized. The conclusions and recommendations of the study are presented in Chapter 5.

2. OBJECTIVES

The objective of the study is to recommend a methodology for assessing the seismic withstand capacity of a NPP such as the Pickering A Nuclear Generating Station (NGS). This methodology may be derived or adapted from the EPRI and USNRC methodologies for assessment of nuclear power plant seismic margin. An implementation plan for the application of this methodology for Pickering A NGS is to be prepared.

3. RECOMMENDED METHODOLOGY FOR PICKERING A NGS SEISMIC MARGIN REVIEW

3.1 INTRODUCTION

Pickering A NGS represents a unique situation and should be treated as such. The nuclear power plant was designed before the current CSA N289 seismic code requirements were available. Since its construction, several parts of the plant that are common with Pickering B have been seismically qualified to the Pickering B DBE. In addition, modifications and upgrades have been designed and engineered according to current seismic design provisions. Because of the construction of several newer CANDU NGSs, such as Pickering B, Darlington and others, there exists a pool of information and data on the seismic design and qualification of similar facilities, systems and equipment. In addition, some of the equipment used in the Pickering A plant is similar to the equipment used in the nuclear industry in other countries which have been qualified by the suppliers to severe seismic conditions.

Knowledgeable individuals that are associated with the design, construction and operation of the CANDU nuclear power plants believe that the Canadian design is conservative, robust and has tremendous reserve strength. This reserve strength is useful when discussing the seismic margin or the seismic withstand capability of the facilities. Several countries have operating plants in similar situations where there was no initial seismic design or have been qualified to lower levels of earthquakes than the current code requirements. A viable approach to establish their seismic withstand capability is by means of a seismic margin review. There exist several approaches for the seismic margin review of NPPs. The most prominent of these basic methodologies are the USNRC and EPRI approaches.

Recent studies by the nuclear industry and the US Nuclear Regulatory Commission (NRC) indicate that NPPs are capable of withstanding earthquake motion substantially greater than the "design" earthquake motion. In May of 1984, NRC formed an "Expert Panel on the Quantification of Seismic Margins" to provide technical guidance and advise on the subject of seismic margins of NPPs. There were three documents produced by the Panel. The first report, entitled "NRC Seismic Design Margins Program Plan"

(Cummings et al, 1984) outlines a proposed NRC program in the area of seismic margins and plans how the Panel's work is to be accomplished. The second report, entitled "An Approach to the Quantification of Seismic Margins in Nuclear Power Plants" (Budnitz et al, 1985), presents a comprehensive review and analysis of the various methods, data, and results of available seismic risk assessments of NPP and other seismic studies. Its aim is to establish seismic margin review guidelines and outline an approach to seismic margin quantification. The third report, entitled "Recommendations to the Nuclear Regulatory Commission on Trial Guidelines for Seismic Margin Reviews of Nuclear Power Plants" (Prassinos et al, 1986) gives detailed guidance on the implementation of seismic margin reviews for NPP. Collectively, the methodology and guidelines contained in these reports will be referred to as the USNRC approach to Seismic Margin Review (SMR) in this document.

Subsequent to the "Panel" reports from NRC, another report on the same subject of seismic margin review was produced by the Electric Power Research Institute (EPRI) entitled "A Methodology for Assessment of Nuclear Power Plant Seismic Margin" (Kassawara et al, 1988). The methodology outlined in that report will be referred to as the EPRI approach to seismic margin review. In general, the EPRI methodology has some similarities with the CSA N289 philosophy.

The current philosophy of SMR of NPPs will be reviewed. This is achieved by first distinguishing the SMR philosophy from other seismic safety studies of NPP such as the Probabilistic Risk Assessment (PRA). Then the USNRC and the EPRI approaches to SMR will be reviewed, outlining their similarity and differences.

3.2 RELATION BETWEEN SEISMIC MARGIN REVIEW (SMR) AND PROBABILISTIC RISK ASSESSMENT (PRA)

In recent years, a number of PRAs have been carried out for NPPs in United States. They include plants at Zion, Indian Point 2 and 3, Oconees, Limerick, Midland 2, Seabrook and Milestone 3. In addition, the NRC funded the Seismic Safety Margins Research Program (SSMRP) at Lawrence Livermore National Laboratory to develop seismic risk analysis methods. The SSMRP methodology was applied to the Zion NPP.

The key elements of a seismic level 1 PRA are: (1) seismic hazard analysis, (2) seismic fragility evaluation, (3) plant system and accident analysis and (4) evaluation of consequences. The level 1 refers to the PRA of the probability of core melt. The outputs of a seismic level 1 PRA usually include: (1) frequencies of occurrence of core melt, (2) identification of dominant seismic risk contributors and (3) identification of the range of earthquake peak ground accelerations that contribute significantly to plant risk. Levels 2 and 3 PRAs refer to the probability of radiation releases and consequences to the public, respectively.

In theory, a seismic PRA can provide complete answers regarding the seismic safety of the plant. In practice, the uncertainties in the risk estimates have been large. These arise from the large uncertainties in the seismic hazard analysis results on one hand, and from the fact that the fragility evaluation relies heavily on analysts' judgement in the absence of actual fragility test data on the other.

In SMR, the concept of High Confidence Low Probability of Failure (HCLPF) is used to avoid some of the problems associated with the use of seismic PRA. The problem of plant seismic safety is narrowed down to the following: given a review level earthquake such as the Seismic Margin Earthquake (SME), the SMR methodology assesses whether the plant can survive the earthquake with high confidence. SMR will establish an estimate of the minimum seismic capacity of the plant. In contrast, seismic PRA gives additional information on seismic capacity in a probabilistic format. A fundamental difference between the seismic PRA and the SMR is that SMR requires a review level earthquake to be specified beforehand. Although a SMR gives less information on the seismic safety of a plant than a seismic PRA, it does provide a high confidence statement of the seismic capacity of the plant.

3.3 USNRC APPROACH VS. EPRI APPROACH TO SEISMIC MARGIN REVIEW

There are a number of areas that are common in both approaches. This is not surprising because the two approaches are not completely unrelated. In fact, many of the major contributors to the EPRI approach are also major contributors to the USNRC approach. In a sense, the EPRI approach can also be viewed as a way to implement many of the

ideas contained in the USNRC approach. In this section, the similarities and differences in both approaches will be discussed.

3.3.1 Similarities Between the Approaches

The two approaches to SMR are similar in four major areas, namely: (a) the definition of seismic margin; (b) the use of the High Confidence Low Probability of Failure (HCLPF) concept; (c) the adoption of a predetermined Seismic Margin Earthquake (SME) level, and (d) the extensive use of plant walkdown technique.

a) Definition of Seismic Margin

Both approaches use the same definition of seismic margin, as adopted by the NRC Panel of Experts (Budnitz et al, 1985). The adopted definition of seismic margin is expressed in terms of the earthquake motion level that compromises plant safety, specifically leading to melting of the reactor core. In this context, margin needs to be defined at the plant level. The margin concept can also be extended to any particular structure, function, system, equipment item, or component, for which "compromising safety" means sufficient loss of safety function to contribute to core melting if combined with other failures.

b) The High Confidence Low Probability of Failure (HCLPF) Concept

Another feature that is common to both the USNRC and EPRI approaches is the use of the HCLPF concept. In the most general terms, the ultimate aim for seismic safety assessment of NPP is to be able to derive the fragility curves for the plant as a whole (i.e. in terms of core melt). These can be determined from the fragility curves for the individual relevant items by mathematical means, assuming all fragility curves of relevant items and their interaction or degree of dependency are known. In practice, however, there is considerable uncertainty associated with the full fragility curves of many individual relevant items. This leads to the adaptation of the HCLPF concept in SMR.

The HCLPF is a conservative representation of capacity and in simple terms corresponds to the earthquake level at which it is extremely unlikely that failure of the component will occur. From the mathematical perspective of a probability distribution on capacity developed in seismic PRA calculations, the HCLPF capacity values are approximately equal to a 95% confidence (probability) of not exceeding about a 5% probability of failure.

While it is possible to derive the HCLPF point from a full set of fragility curves, it is not necessary to use this procedure in every case. The HCLPF values for specific types of components are expected to be derived from a combination of engineering data, either test data or data from real earthquake experience, engineering analysis and judgement. In general, it is easier to identify this point directly, and there is more confidence in the identification of this point than in the identification of the median, randomness and uncertainty parameters which would be required to derive the full fragility curves. A group of engineers are more likely to agree on a ground motion level associated with the high confidence of low probability of failure of a component, although they are not likely to agree that the confidence can be expressed exactly as 95%-5%. This is the reason that the HCLPF concept is a more practical way to deal with the whole question of seismic margins than an approach using the median fragility values.

c) Seismic Margin Earthquake Level

Both approaches adopted the philosophy that a predetermined seismic margin earthquake (SME) level is given. This SME level serves as a benchmark upon which the seismic margin of the plant is compared. If the plant level HCLPF is evaluated to be larger than the SME level, the plant is considered to have adequate seismic margin against the occurrence of SME. If the plant level HCLPF is found to be lower than the SME level demand, one still obtains a numerical value of the plant seismic capacity at a high confidence and low probability of failure level.

d) Plant Walkdown

Both approaches employ the plant walkdown technique in the review process. The purposes of the plant walkdown(s) are as follows:

(i) to identify or confirm the frontline and supporting systems required to perform necessary functions for plant shutdown;

(ii) to pre-screen from the margin review all elements identified in (i) for which the HCLPF levels exceed the SME demand level, based on combined experience, judgement, and use of earthquake experience data as appropriate. Budnitz et al (1985) provided a fairly comprehensive list of components and their generic HCLPF values which can be used as guidelines.

(iii) to clearly define the failure modes of elements that are not pre-screened in (ii) and need more detailed seismic margin assessment (SMA), and

(iv) to identify items that can cause system interactions (SI) affecting the elements. SI refers to the adverse effects from the response of one component or system on another.

The SI that are of concern to SMR are proximity, II/I and flooding. Proximity refers to the potential adverse effect from the seismic motion of one component on another with a resultant loss of safety function. It is applicable for both equipment to equipment, and equipment to structures. Equipment as used herein includes mechanical and electrical components (pumps, valves, control panels, switchgear, etc.) as well as distribution systems (pipe, conduit cable trays, etc.). The arrangement or routing of seismic Category II (or non-seismic qualified) supported components over Category I (qualified) components, II/I, could potentially lead to loss of safety function of the Category I component if the Category II supported component should lose its structural integrity or experience excessive motions. Flooding can result from the loss of function or integrity of either Category I or II components, and be initiated by either proximity, II/I, or other seismic design weaknesses.

In summary, to screen out the obviously rugged elements, and to identify elements that need SMA work are the main objectives of plant walkdowns.

3.3.2 Major Differences Between the Approaches

There are two major differences between the USNRC and the EPRI approaches, namely (a) the method of expressing systems that are required to achieve and maintain a safe shutdown condition and containment of postulated radiological releases following a seismic margin earthquake, and (b) the methodology to arrive at the HCLPF capacity of the components, and ultimately the plant itself.

a) <u>Safety Systems</u>

The USNRC approach uses fault tree and event tree analyses to display the safety systems activity, and uses a combination of probability and Boolean algebra to arrive at the overall HCLPF capacity of the plant. In the EPRI approach, the mode of systems operation following a SME is presented in the form of Success Path Logic Diagram

(SPLD). Such a diagram identifies in a series-parallel fashion those functions (or systems) that, if successful, can achieve and lead to a safe shutdown condition and containment of postulated radiological releases after a SME. By their nature, the SPLDs are developed in "success space", as opposed to "failure space" commonly employed in fault tree and event tree analyses. The SPLD, fault trees and event trees express the same information. One of the advantages of using the SPLD approach is that it is a more direct method of presenting the information. Another advantage is that the SMR can be restricted to a smaller number of safe shutdown paths, as suggested by the EPRI methodology, instead of covering all possible paths of required safety functions. This will reduce the number of elements that need to be reviewed.

The success path logic diagrams do not lend themselves to quantification, whereas event trees and fault trees are directly quantifiable (although with a considerable error margin). However, the element-level seismic capabilities are to be evaluated by purely deterministic methods in the EPRI approach so that no plant-level quantification needs to be done other than the statement that the seismic capability of a given success path is simply the seismic capacity of the weakest element in the path.

b) Seismic Margin Assessment Methodology

It is necessary to establish the HCLPF capacity of the elements that are identified as required safety functions of the plant after a SME, but are not prescreened out during the plant walkdown process. There are two methodologies for calculating the HCLPF capacity of elements: the Fragility-Analysis Method and the Conservative Deterministic Failure Margin (CDFM) method. While the USNRC considered both methodologies to be acceptable, the EPRI approach definitely prefers the CDFM method. An outline of each of these two methods is presented below:

(i) Fragility-Analysis Method

This method is a probabilistic way to obtain the HCLPF values. The fragility of a component is assumed to be lognormally distributed, expressed in terms of three parameters, namely, the median capacity and logarithmic standard deviations. These logarithmic values represent the randomness in the capacity and uncertainty in the median value (Cover et al, 1985). Based on the definition of HCLPF (i.e., 95% confidence of not exceeding about a 5% probability of failure), the HCLPF values can

be obtained. In lieu of explicitly determined logarithmic values, the HCLPF value may be conservatively estimated by adopting the value of 0.8 for the sum of the logarithmic standard deviations. This gives an HCLPF value approximately equal to 0.25 times the median capacity. The main drawback of this methodology is that some statistical data needs to be available before the median value can be confidently used.

(ii) The Conservative Deterministic Failure Margin (CDFM) Method

This is a deterministic way to obtain the HCLPF value for the element, overcoming some of the drawbacks associated with the Fragility-Analysis Method. It is the method advocated by EPRI in their approach to seismic margin assessment.

In this approach, the SME demand is computed with conservatism only introduced at the specification of the ground input response spectrum, i.e. in the definition of SME. The SME should be established based on the mean plus one standard deviation (or the median as is currently practised) rather than the mean level. It is argued that with the SME conservatively defined, there is no need to add additional conservatism in the lesser uncertain response parameters. Therefore, damping, structural modelling parameters and soil-structure interaction evaluations should all be median-centred. Also the SME load should be combined with normal operating loads (NOL) only with a load factor of unity. Because different factors of conservatism are used in obtaining the seismic design demand (DBE demand for Canadian NGS) and the SME demand, it is possible that for some elements, the SME demand is less than the DBE demand, even though the specified SME level is higher than the DBE.

On the other hand, the element seismic capacity must be conservatively estimated for comparison with the estimated SME demand. There should be higher confidence that there is less than a 5% probability of failure even if the SME demand is reached. If the SME demand, throughout the frequency range of interest, is less than or approximately equal to the design demand for which the element has been previously designed and qualified, no further work is necessary in order to demonstrate capability to withstand SME. If the SME demand significantly exceeds the design demand in an important frequency range or where the element has not previously been seismically qualified, seismic capacity evaluation of the element becomes necessary. Capacity for items such as anchorages and tanks can be evaluated analytically. For electro-mechanical

equipment, the functional failure modes generally have to be assessed using test and experience data. Component specific qualification (proof) or fragility test data may be used for this purpose. Alternatively, a generic equipment ruggedness spectrum (GERS) may be used. GERS are intended to represent the 5% damped test response spectra (TRS) or experience response spectra (ERS) available for a specific type of equipment for which no failures were observed. GERS are always set lower than the lowest TRS for which failures were observed, if any failure test data exists.

The Conservative Deterministic Failure Margin (CDFM) approach can be considered as a practical way to estimate and define the HCLPF level of elements. The seismic capacity of the element is conservatively estimated (less than 5% probability of failure). This depends on some convincing evidence that the 5% probability level is demonstrated not to be exceeded, which is difficult. In addition, it is unlikely that the computed SME demand will be reached because the demand is computed using ground response spectrum based on the mean plus one standard deviation (or the median). The net result of such a combination of conservatively defined seismic demand, median centred response to the demand and a conservative strength prediction is in accordance with the HCLPF concept.

For each element which has not been previously pre-screened and is subjected to SMA, the end product of the assessment is either: (a) a statement together with backup documentation that the element has a capacity in excess of the specified SME level, or (b) a determination (with backup documentation) of the earthquake input level for which the capacity exceeds the demand. This earthquake input level for an element is obtained by linearly scaling the input spectrum downward over all frequencies until the demonstrated element capacity exceeds the demand. It should also be understood that all seismic capacities are developed in terms of peak ground accelerations. Hence it is usually necessary to establish the basis for floor response spectra development in order to be able to translate actual seismic capacity of a component to its equivalent capacity related to ground spectra demand.

Using the EPRI approach, the HCLPF capacity should be documented for all elements within a success path. The element with the lowest SME capacity in a success path establishes the SME capacity of that success path.

3.4 EVALUATION OF USNRC AND EPRI APPROACHES AS APPLIED TO PICKERING A NGS

Broadly speaking, the USNRC approach is a more general approach. By viewing the required safety functions of the plant due to a postulated SME in terms of event trees and fault tree diagrams, this approach presents a more complete picture of the many ways that the plant can maintain required safety functions. As a consequence of this generality, it is likely that a larger number of elements will need to be reviewed. On the other hand, the EPRI approach, which narrows down the process after SME to one or two success paths, appears to be a more practical approach. Less elements will be involved in the review process. This in turn can focus more of the SMR effort to the essential elements in the success path. This concentration of evaluation effort should increase the reliability of the HCLPF estimation for the plant.

Using the Fragility-Analysis method to obtain the HCLPF values of elements, the USNRC approach assumes that there exists a database of performance data on different elements so that the median value can be determined by statistical means. The deterministic approach (CDFM method) advocated by the EPRI approach is a more practical approach if one does not have an extensive database on the seismic performance of various elements that need to be reviewed.

In the use of fragility data and HCLPF capacities of elements, it is important to demonstrate that the data and experience are applicable. The seismic performance of an element is dependent on the method of mounting, anchoring, elevation, type of foundation, piping and electrical connections (top or bottom, rigid or flexible, supported or free). In addition, the limitations of using peak ground acceleration (PGA) as a single parameter to measure capacity should be viewed with due caution. The PGA capacity of an element may vary with several factors such as the frequency content and duration of ground motion. To successfully apply the experience database, close correlation with the Pickering A elements and conditions should be assured.

An alternative to the use of the fragility analysis method in screening out robust equipment is by analysis, testing, redesign and bolstering-up (restraints, stops, stronger legs or brackets, supports and anchors, etc).

Many of the recently conducted PRAs in the US indicated that the risk from external events such as earthquakes could be a significant contributor to the core damage in some instances. A policy for individual plant examination of external events (IPEEE) is being formulated (NUREG/CR - 5259, 1990). The general objectives are: 1) to develop an appreciation of severe accident behaviour, 2) to understand the most likely severe accident sequences that could occur at the plant, 3) to gain a qualitative understanding of the overall probability of core damage and fission product releases, and 4) if necessary, to reduce the overall probabilities for core damage and fission product releases by modifying where appropriate, hardware and procedures that would help prevent or mitigate severe accidents. In the evaluation of seismic events, the IPEEE policy considers both the seismic PRA (level 1 plus containment performance) and the seismic margin methodology as viable approaches to identify potential vulnerabilities. The policy recommends methodology upgrades to include relay chatter, soil liquefaction and plant walkdown enhancements for USNRC method, guidance on alternative success paths for the EPRI method, and nonseismic failure and human actions for both methods.

Pickering A NGS was the first of the currently operating CANDU plants. At the time of its design, there were few seismic requirements specified for its safety systems. As a result, the success path approach suggested by EPRI, together with the deterministic approach for seismic margin assessment (CDFM Method) would be a more viable approach to SMR for this plant. A few modifications to the methodology can be adopted to make use of the experience gained from margin reviews and to adapt the process to the CANDU system and local site conditions.

On the basis of the review of the seismic margin methodologies and the Pickering A NGS design and systems, the recommendation is that the EPRI approach be modified as necessary and applied to the possible seismic margin review of the Pickering A plant. The EPRI methodology is judged to be the most suitable to apply to Pickering given all the unique features of this particular facility.

3.5 RATIONALE FOR THE SELECTION OF EPRI METHODOLOGY

The Pickering A NGS was designed in the sixties when the seismic design requirement was based on the National Building Code of Canada. Since then, it was followed by Pickering B, Bruce A, Bruce B and now Darlington NGS. Pickering B and Darlington which is a short distance away, have been designed to the increasingly strict seismic design requirements of the current CSA N289 code. Some of the Pickering B structures and systems are common with Pickering A and have been qualified to the more stringent seismic code requirements. In addition, there were similar systems and equipment to those used in Pickering A which have been subsequently qualified in the Pickering B design. All the modifications, retrofits and additions to the Pickering A structures and systems are subject to the current codes of seismic analysis and qualifications. These conditions raise a unique situation at the Pickering A NGS. Some systems and equipment are seismically qualified to the DBE level (not the margin earthquake), some can be qualified by comparison to the more modern designs of Pickering B or Darlington stations and some systems were designed before current seismic codes with no specific experience to judge their seismic withstand capability.

In the EPRI approach, the mode of systems operation following a SME is presented in the form of a SPLD. An advantage of using the SPLD approach is that it is a more direct method of presenting the information, and is more easily understood by engineers who have not been exposed to the probability risk assessment technique. Another advantage is that one can restrict the seismic margin review to a smaller number of paths of safe shutdown. This will reduce the number of elements that need to be reviewed.

It is practically very difficult to redesign and retrofit an older station to bring it up to the seismic qualification standards that are recommended by the currently available codes. A much more manageable approach and one that meets the essential safety requirements is to limit the seismic evaluation to the most essential safety systems and sequence of operations that identify a success path. The success path is defined as the sequence of operations and associated structures, systems and components required to shutdown the reactor, dissipate decay heat, contain the radioactivity and monitor and control the reactor systems. This success path can be qualified and retrofitted to withstand the margin earthquake that is selected for the review. This methodology is

deterministic, limited in scope and is expected to be sufficiently rigorous to provide the qualifications of the essential safety and success path functions to withstand the postulated margin earthquake. These features are essentially those of the EPRI approach.

The EPRI approach is fairly practical, direct and appears to be reliable in evaluating the seismic safety of the systems and components. The methodology will specifically qualify a success path to some engineering criteria for the selected margin earthquake. All other systems may be assumed to have ceased providing their intended design functions. In using the EPRI approach, many of the major structures and components that are robust and appear to have a high reserve strength can be eliminated from detailed seismic margin review. In addition, many systems and components can be qualified by database comparisons with other designs and qualified processes in existing NPPs. It is important that these databases are demonstrated to apply to the Pickering A plant. The selection of the deterministic EPRI approach was also due to the lack of confidence in the available limited performance database for different elements and the probability of their failures. Some of the available fragility data and HCLPF capabilities of elements may not be directly applicable to all situations given that the anchor and construction methods are different. The EPRI approach is concerned with the qualification of the success path systems and components which if limited to safety systems as proposed, is limited in scope and requirements for performance databases.

3.6 SUMMARY OF PROPOSED VARIATIONS TO EPRI METHODOLOGY

There are some significant differences between the Canadian and US NPP design, operation and seismic qualification requirements. Some of the major differences between the Canadian and US NPPs include:

a) The Canadian CANDU NGS system uses heavy water whereas most US NPPs are of the pressurized water reactor type. As a result of this fundamental difference, differences exist in all areas of process, design, equipment, safety systems and plant operations.

b) The historical seismicity of a site in Southern Ontario which is dependent on area tectonics, earthquake mechanisms, the characteristics of ground motion and seismic hazard may be similar to that of a nearby NPP sites in US where seismic hazard evaluations have been conducted. However, the local site specific characteristics of an area such as Pickering may be unique and should be taken into account in the establishment of the margin earthquake.

Because of the differences between the Canadian and US NPPs, modifications were made to the EPRI approach to suit the Pickering A conditions. Some of these variations include:

a) Definition of the Margin Earthquake.

The EPRI methodology suggests four alternative approaches for the determination of the seismic margin earthquake (SME). Three of the four approaches require the selection or determination of a peak ground acceleration (PGA) level. No guidance is given for the determination of the appropriate PGA level. The fourth approach links this with some assumed level of annual probability of exceedance. Following some rationalization, EPRI suggests a SME level corresponding to PGA of 0.3 g (or in some cases 0.5 g) as a conservative upper bound to accommodate individual site characteristics.

The proposed methodology for the determination of the Margin Earthquake (ME) takes into account the seismo-tectonic features of the area, local geology, and site specific conditions. This is done by performing a state-of-the-art seismic hazard analysis and developing a site-specific uniform hazard spectrum at a recommended median of 10^{-4} per annum. Lower annual probabilities of exceedance are not credible especially in eastern North American locations. The ME may also be described in terms of several ground response spectra corresponding to earthquakes of several magnitude-epicentral distance combinations.

b) Composition of the Review Team.

The proposed seismic margin review team is identified on the basis of the known features of the CANDU system and its design. The team may consist of 6 people - one operator, one mechanical systems engineer, one electrical systems engineer, one earthquake design engineer and two seismic

qualification and review engineers. These members of the review team should be well informed and have a general knowledge of plant systems and functions, plant design, operations, maintenance, nuclear design standards and procedures, knowledge of structural performance and failure modes, ability to perform fragility and margin type evaluations and understanding of the seismic probability risk assessment. The input from operators is necessary for the determination of the success path(s). The review team should include support personnel as needed. The EPRI methodology identifies the seismic margin assessment team to consist of 3 to 5 members with less emphasis on input from the operators and support staff.

c) Systems and elements in a likely success path.

Without getting into many details at this stage, it is clear that the shutdown and safety systems, containment and cooling of the CANDU design are quite different from other NPP systems.

d) Qualification of equipment and systems by comparison with the newer Pickering B, Bruce and Darlington Plants.

The proposed methodology for prescreening of structures and components of the Pickering A NGS requires that all containment systems be qualified by analysis or comparison to a similar system that has been qualified to the ME level. It is also proposed that testing of equipment similar to that in the plant be adopted for the purposes of confirming functionality under ME conditions. Other details of the EPRI seismic margin assessment prescreening procedures can be applied to the Pickering A NGS.

e) Loss of coolant accident (LOCA) assumption.

In the EPRI approach, a small or minor LOCA may be assumed. However, in the Pickering A case, components of the primary heat transport system will have to be seismically qualified to the ME level in order to ensure that no LOCA would occur as the resutl of the earthquake. Adequate analysis should be made before the assumption of no LOCA is adopted. It should not be ruled out that it may be easier to qualify a success path assuming a LOCA occurs than to qualify the heat transport system such that a LOCA can be assured not to occur. However, this is a question to be decided on during the seismic margin review study.

f) The human factor.

An important factor in the performance of the safety functions is the human factor which relates to the performance of the operators under the stressful conditions of the postulated margin earthquake. Operator's education and qualification is stressed.

g) Proposed IPEEE policy upgrades.

Upgrades to the EPRI approach as proposed by IPEEE policy are adopted. These include evaluations of relay chatter, soil liquefaction and the consequences of seismic failure such as loss of off site power.

4. IMPLEMENTATION PLAN

4.1 INTRODUCTION

The responsibility for conducting the seismic margin review study should rest with the utility. The operating entity of the nuclear facility should be assisted by competent personnel in various areas of seismology, earthquake engineering design and qualification, and seismic margin review. The utility personnel are in the best position to lead the study. Experienced individuals with knowledge of the nuclear generating station operations and familiarity with the safety systems are part of the review team. Input from specialized areas such as operations, systems engineers and seismic qualification engineers are also needed. Because of the importance of the review both in technical and public confidence terms, the inclusion of competent, reputable outside consultants to the utility on the review team would be advantageous. The procedures adopted are those of EPRI with modifications to suit the existing CANDU NPPs such as Pickering A. The seismic margin review procedure consists of the following steps:

(a) Selection of the review team.

(b) Adoption of the earthquake level appropriate for the SMR, namely definition of the Margin Earthquake (ME).

(c) Definition of the performance criteria.

(d) Specification of the success paths in terms of operational procedures, equipment and systems. Development of a list of the possible variations and minor alternate process decisions.

(e) Elimination of the systems and components that have already been seismically qualified to the DBE with obvious robustness of construction and reserve strength to qualify for the review earthquake conditions.

(f) Elimination of equipment and systems that are qualified or that are identical to equipment that is seismically qualified by suppliers to levels and earthquake conditions that are equal to or exceed the ME. Examples include equipment used in the nuclear industry in the United States that may be qualified to SME of peak ground acceleration of 0.3 g.

(g) Conduct one or more field inspections as needed to identify marginal systems for the seismic margin assessment.

(h) Performance of the qualification and review work for all identified marginal systems and identify the weak links in the success path.

(i) Documentation and reporting.

In this Chapter, the implementation plan for the proposed methodology with recommended modifications will be reviewed.

4.2 SELECTION OF THE REVIEW TEAM

The composition of the review team should include various design and operation specialities in addition to seismic qualification engineers. The necessary talents required for the review team include:

a) Plant operations personnel

The plant operations personnel are knowledgeable about normal and emergency operating procedures. They are trained and familiar with the operator's likely response to abnormal situations. Selected personnel should be conversant with the safe shutdown systems, instrumentation, controls and the possible success paths for the reactor shutdown, cooling and containment in case of emergency conditions. The plant operators are to be part of the review team for as long as needed but at least until the success paths are determined and the operator's response and function under the margin earthquake conditions has been considered.

b) Systems engineers

The systems engineers are responsible for identifying all reasonable alternative procedures to bring a plant to a maintained stable condition. Systems engineers are also expected to be familiar with all frontline and support systems and components. These systems include all electrical, hydraulic and pneumatic systems. It is the primary responsibility of systems engineers to select the preferred and, if possible, an alternative success path in detail. The team should include electrical and mechanical systems engineers.

c) Seismic qualification and analysis engineers preferably with seismic field inspection experience.

The seismic qualification engineers should be familiar with and experienced in

one or more of the following areas:

- All relevant and applicable codes and standards for the seismic design of structural and mechanical systems and components.
- Modes of failure of electrical, mechanical and structural systems during a major earthquake event.
- Dynamic analysis and earthquake engineering design.
- The seismic design and qualification of various systems and components in the Pickering A and B as well as the Darlington stations.
- General knowledge of plant structures, systems and functions.

A reasonable team may consist of six people - one operator, mechanical systems engineer, electrical systems engineer, an earthquake engineering designer with experience in the design of the newer CANDU nuclear stations, and two seismic qualification engineers. Once the review team is selected, the immediate tasks are the definition of the margin earthquake and setting the performance criteria and to determine how they are met.

4.3 DEFINITION OF THE MARGIN EARTHQUAKE

In terms of the seismic margin review, the ME is defined as the selected seismic loading at which the capacity of the NPP to survive is determined. In considering whether or not there should be a specified relationship between the ME and the DBE, it is useful to review the distinction between a margin review and the seismic design process.

The seismic margin review will address the ultimate capacity and survivability of success path structures, systems and components. All other systems and structures will be assumed to have ceased to perform their design functions.

The seismic design provisions of the building codes are normally formulated with the philosophy that no damage should occur during a minor earthquake. During a major event, adequate ductility should be provided for in the structure such that no collapse or loss of life occurs. The maximum or ultimate capacity is not addressed by the code. Extensive use is made of previous experience with the performance of structures during

earthquakes which is used to calibrate the code design provisions. This philosophy of design is completely different from the concept of margin or withstand capacity. Although the members are designed for the ultimate state load, it is understood and recognized that the structure itself has a capacity well beyond the design loads because of inherent conservatism in many of the design assumptions. However, the design process is neither capable of nor expected to determine how much overcapacity exists.

If there is any question as to the actual capacity of the structure, this can be determined by conducting a load test (real or simulated) in which the response of the structure is determined for some limit load in excess of the design load. A simulated load test would involve an inelastic analysis to determine the extent of response (e.g. top deflection) of the structure when subjected to the limit load. In the nuclear power plant situation, the SMA procedure is directly analogous to a simulated load test, in which the margin earthquake and its characteristics correspond to the limit load.

It can be seen that these margin or capacity assessments have little or nothing to do with the original design force (or DBE, in the case of a NPP) which is used to design, and build the facility. Consequently, it is not necessary that there be a relationship defined between ME and DBE. In fact, since the remainder of the margin assessment process uses different methodologies than may have been used in the original design process, the relationship between the ME and DBE may well be more apparent than real.

At this point, it is sufficient to define the ME as being somewhat larger than the highest DBE level which was used in the design of the Pickering B or the Darlington plants. The characteristics of the ME should represent the characteristics of a high level potential earthquake that could be expected to occur at the site.

The selection of the margin earthquake should be made by a panel of experts consisting of representatives from the utility and the nuclear regulatory authority as well as seismologists and seismic qualification engineers. The decision should be guided by the seismic activity of the region, the site specific characteristics and seismic hazard.

The margin earthquake should be specified in terms of two orthogonal horizontal time histories or ground response spectra and one vertical time history or ground response

spectrum. The associated damping value may be selected in the 5 to 10% range (normally 5%). In practice, a single horizontal response spectrum is specified for both orthogonal horizontal directions. The vertical response spectrum may be specified by a ratio to the horizontal spectrum, although the unusual frequency content of vertical motion would suggest that a distinct separate spectrum be defined for vertical motion.

Although it may be reasonable to suggest that the effect of aftershocks be included in the margin review, practical considerations make this very difficult to implement. Following the main shock of a margin earthquake, the elements of the plant are in an undefined state of deformation and severe inelastic stresses. Without a defined starting state of the element, available state-of-the-art analysis techniques are incapable of producing meaningful results.

To represent the low probability of occurrence event and to reflect the site specific characteristics, two basic techniques are proposed as alternatives for the specification of the ME. Following the determination of the ME for a particular site, it would be prudent to link the proposed approaches to the EPRI approach and correlate the results with the seismic hazard studies conducted for neighbouring or similar sites. Discrepancies with available studies should be justified.

4.3.1 The Deterministic Approach

One alternative is to specify the ME in terms of defined PGA level. A spectrum is anchored to this PGA by using a set of 84% NEP (non exceedance probability) spectral amplification factors. These amplification factors may be site specific (preferable) or generic to the particular geographical region. Current practice is to use the median instead of the 84% NEP spectral values.

In this approach, a set of appropriate ground motion time histories are normalized to the selected PGA and the median level determined by examining the distribution of spectral ordinates at each natural period. This process can incorporate the site specific characteristics of the ground motion through selection of time histories which are appropriate for the particular seismo-tectonic environment. The resultant response spectrum is not a uniform hazard spectrum. The simplicity of this approach is a trade off against the introduction of a degree of conservatism at the lower frequency range.

As an alternative, a generic or site specific Uniform Hazard Spectrum (UHS) is determined at some low level annual probability of exceedance (APE). There will be an explicit PGA* associated with this UHS. The UHS may be scaled by the ratio PGA/PGA* to determine the ME spectrum.

4.3.2 The Probabilistic Approach

The approach described in this section is a process for the determination of what is referred to as a spectral ME. Seismo-tectonic regions in which seismic activity could produce strong ground motions at the site are evaluated. The objective is to determine one or more pairs of M-R (magnitude-epicentral distance) without regard to any annual probability of exceedance, which dominate the maximum seismic hazards at the site. It goes beyond the scope of this report to specify further the details of the seismological investigations which would be necessary to determine the maximum M-R pairs. Needless to say, such investigations would need to incorporate state-of-the-art, peer reviewed, seismological research and take into account the most up-to-date information on fault structures, etc. For a particular site, both farfield and nearfield seismic motions would need to be considered. It is important to ensure that different sources of motion are maintained separately, both as M-R pairs and in subsequent analysis.

Consistent with the EPRI SMA methodology, a 84% NEP or median level ground response spectrum (GRS) is to be determined for each M-R pair. Several possible methodologies may be used for such determination. These include the empirical approach of utilizing ensembles of appropriate time histories and approaches utilizing wave propagation from the source to the site (e.g. Boore & Atkinson, 1987). For maximum confidence, it is desirable that results from several alternative approaches be calculated and compared. These GRS may further be scaled to match a generic or site specific UHS at some low level APE at the fundamental frequency of the structure f_o.

At the completion of the first stage, the ME is defined by several GRS (or spectra scaled to match UHS at frequency f_o). For purposes of subsequent discussion, let us assume that there are two spectra which will be referred to as GRS_1 and GRS_2. These spectra are deliberately <u>not</u> anchored to a specific PGA (even though such may be inferred by high frequency spectral ordinates). However, it is desirable to have some "intensity-type" indicators by which to describe these spectra. Assuming, that the NPP structure is on a

rigid base which is placed directly on rock, then let us define the fundamental structural frequency as f_o. One can further define the spectral ordinates of GRS_1 and GRS_2 at frequency f_o as S_{a1} and S_{a2}, respectively. These latter quantities represent the real seismic loads on the structure and are therefore defined as the spectral MEs. This process may be repeated for various structures in the NPP.

4.3.3 Linking the proposed approaches to the EPRI approach

The second stage can be applied to both approaches 4.3.1 and 4.3.2, and is concerned with linking the procedure more directly to the upper/lower bound EPRI approach which is done through the specification (in EPRI) of a specific PGA (normally 0.3g or 0.5g) for the SMA. As indicated previously, this specific PGA is used to anchor a GRS shape or scale a UHS. This second stage requires the development of the relationship between the two spectral MEs determined above and the EPRI-type SME. In our view, the second stage of the ME process is optional. However, given that the experience for the evaluation of components in Canadian plants may make use of databases from U.S. plant experience, the development of spectral relationships between the different types of MEs may result in a significant reduction in work.

Another reason for at least considering the second stage of the process is to be able to have a qualitative assessment of the extent of the difference between ME generated as per the recommendation in this report and that obtained by the more-or-less standard EPRI procedure. A comparison of spectral MEs and SMEs (i.e. ordinates at natural frequency f_o) would give some indication as to whether the margin earthquake conditions obtained from this evaluation differ significantly from those which are implicit in EPRI-type SMEs.

Following either of the discussed alternatives, it is possible to define the ME in terms of GRS and PGA. It would be prudent to evaluate how this information correlates with available studies especially in neighbouring US locations. As an example, a seismic hazard study has been conducted and SME determined for the Ginna NPP near Rochester, NY, which is about 120 km from the Pickering A NGS site. Major discrepancies between results of studies on nearby sites should be addressed and explained.

During the process of determining the ME in terms of GRS, it is possible to select actual time histories from the available strong motion database. The time history selection should be guided by previous records at or near the site, the regional tectonics, source mechanisms and site conditions. The time histories have the advantage of providing realism and design convenience. From an engineering point of view, time histories are more suited to nonlinear and inelastic analysis of structures.

4.4 SYSTEMS AND ELEMENTS IN A LIKELY SUCCESS PATH

During and following a severe seismic event, sufficient functional capability must exist to: a) shutdown the reactor and maintain it in a shutdown state indefinitely, b) remove decay heat during this shutdown period, c) maintain containment to limit radioactivity release, and d) monitor and control. Most of these functions are the basic requirements of all nuclear seismic codes although the methodologies for implementation may differ. In most countries, there is in addition to safety requirements a requirement that the plant must be able to operate during and following an event up to some level of site motion severity called the operating basis earthquake (OBE). In Canada, no such requirement exists. The seismic design approach in Canada is given in CSA N289. It is a methodology based on "success path" although such terminology was not used in the writing of the code.

The definition of the success path is those structures, systems and components required in a viable operational procedure to perform the necessary safety functions and to bring the plant to a stable condition (either hot or cold shutdown) and maintain that condition for as long as needed. This involves the removal of decay heat and monitoring and control functions. In addition, it is essential to contain all sources of radioactivity and prevent any significant releases to the environment. The selection of the success path is a joint responsibility of the plant operators, systems engineers and seismic qualification engineers involved in the margin review study. A single success path is ultimately all that is required. However, examples of actual seismic margin assessments in the U.S. nuclear industry indicate that it is prudent to evaluate several paths and no less than a preferred success path and an alternative. The following is a discussion of the possible scenario following the ME and the systems and elements in an example success path.

Following a major seismic event, it is necessary to ensure that the containment boundary will continue to perform its designed functions and not fail. Following the earthquake, isolation of the containment is initiated automatically if containment building pressure or activity levels are exceeded, or by safe failure to the closed position after total or partial loss of power supply to the logic circuits. Containment isolation is achieved by the closure of all open penetrations. The same result can be achieved manually by the operator.

Upon the loss of class II power or the receipt of a signal from one of 9 sets of sensors, the shutoff rods will drop into the core. This guarantees the reactor shutdown. The shutdown system includes the trip system, shutoff rods and moderator dump. The primary heat transport system should be qualified to withstand the margin earthquake and continue to dissipate the decay heat. As an alternative scenario, it is possible to consider a loss of coolant accident if the primary heat transport system is assumed to cease performing its design function after the margin earthquake. Another scenario is to assume that emergency power or emergency cooling water cannot be supplied. In this case, the heat sink will be the moderator system. Fuel heat will be removed by evaporation of the fluid in the calandria. A source of make up water to the calandria needs to be provided to ensure long term cooling. The emergency coolant injection system (ECIS) can be used for emergency core cooling.

Another condition that can also lead to the use of the moderator as a heat sink is the rapid depressurization of the boilers. This condition will cause void formation in the primary heat transport system. Refilling the system using a manually controlled pressurizing pump cannot be done for half an hour after the earthquake. Under void conditions, thermosyphoning cannot occur. Again this results in a similar situation to the loss of coolant by the assumed failure of the primary heat transport system.

Under conditions when the moderator is used as a heat sink, it will evaporate and will continue to boil off and deplete the inventory in the calandria. Make up water can be added to the moderator. Water which evaporates from the calandria will condense inside containment and collect on the reactor building floor. Condensate collected inside containment is circulated to maintain the required level of water in the calandria.

When no water feed to the steam generator is assumed, there will conservatively be sufficient water in the steam generators to remove the primary heat for half an hour. The emergency water supply can be started within half hour to ensure continuous cooling of the fuel without loss of the primary heat transport inventory. The emergency water will come from the boiler emergency supply tanks. After that, the boiler level can be maintained using the emergency water supply. The boiler emergency cooling system will adequately cool the steam generator for about an hour. The control system is of particular importance since it provides the sensor data and signals for control functions.

From the discussed scenarios following a ME, a success path may include the containment, the shut-off system, primary heat transport system or the emergency coolant injection system and all associated controls and equipment. Detailed determination of the success path and alternate path and the definition of all structures, system and components involved, is an important part of the seismic margin review.

4.5 SPECIFICATION OF SEISMIC MARGIN REVIEW OBJECTIVES FOR VARIOUS ELEMENTS

A criterion of performance needs to be developed for each component of the success path to be reviewed for seismic margin. To plan for this task, information is needed concerning the component, applicable codes and standards used in the design, material properties and data for structures and components and the function that the component is expected to perform in the success path. The following are a few examples and by no means a comprehensive list:

4.5.1 Civil Structures

- Assess capability to survive the ME. The criteria for evaluation of a particular structural system should include: strength, deflection and deformation, function, stability, dynamic and fatigue effects, as well as strength and performance of the foundation soils.
- Structural integrity and crack width to limit postulated radioactivity release.
- Damage or failure of unqualified structures should not cause qualified components to cease performing their design functions.

- Access to needed equipment and systems should remain clear.
- Cascading or spatial interaction effects should be assessed.
- Consequential events such as LOCA, flooding and fires should be considered.

4.5.2 Electrical and Mechanical Equipment

- Sensors and relays should function during and following the ME event.
- Mechanical equipment should maintain integrity, anchorage, connections and operation.
- Electrical components should maintain function and control.
- The potential failure of unqualified systems or equipment should not result in failure of qualified equipment or systems.
- Availability of power supply or unimpaired manual operations should be assessed.
- The consequences of relay chatter and irrational behaviour of unqualified systems should be considered.
- Consequential events if postulated should be evaluated.

4.5.3 Subsystems

These subsystems include piping, cables and cable trays, conduits and HVAC ducting.

- Essential piping, cables and instrument lines should remain intact and functional.
- Large earthquake displacements should be accommodated in the anchor and support design.
- Relative movement at connections (piping, tubing, etc.) should be accommodated.
- Connection of pipes into vessels, heat exchangers and other anchor methods is a particularly vulnerable location due to the pipe flexibility and rigidity of the connection, and proximity of valves to structures.
- Subsystems should not fail due to failure of unqualified structures or the failure of unqualified equipment or other subsystems.

4.6 IN-PLANT FIELD INSPECTION SURVEYS

In the process of the proposed seismic margin review, one or more plant field inspections may be required. The initial inspection visit is conducted for the purpose of selecting a preferred success path and, if possible, one alternative success path for the seismic margin review. It is possible during this process to eliminate those components or paths which appear to be difficult and potentially uneconomical to evaluate for seismic adequacy at the ME level. This inspection should be conducted by the system engineers, an experienced operator and one or more members of the review team.

The success path that is selected as the preferred path is one which the plant operators would follow based on training and procedures. It is preferable to consider a few success paths. If too few paths are selected, the seismic margin review may require several iterations and could take longer to perform and would result in a greater cost in attempting to qualify marginal components. On the other hand, selecting too many success paths will make the seismic margin review study not cost effective. It is recommended that a preferred path and, if possible, an alternative path should be evaluated by the seismic margin review study.

In the initial plant inspection, it is necessary to identify the sensors, transmitters, relays, recorders and instrumentation required for the safe shutdown of the reactor, removal of decay heat, containment of radioactive releases, and the monitor and control functions.

A second plant inspection may be conducted by the seismic margin review team to:

- Prescreen from the margin review all components and systems that have been previously qualified from experience and judgement as appropriate.
- Define the failure modes of elements and components that were not prescreened.
- Define the potential problems from SI and consequences of failure of the unqualified components such as unreinforced masonry walls.

The review team should visit all components of the selected success paths that are accessible. These include distribution systems such as piping, cable trays, conduits and HVAC ducting. It is only necessary to inspect one component among several that are

judged to be similar. The review team can identify inaccessible components for qualification by analysis. Visual field inspection may assist in the various aspects of pre-screening, definition of failure modes and identifying potential problems with SI.

It is possible to combine the first and second inspections, the advantage being that all the review team will be together. This will help narrow down the selection of success paths. However, more preparation and more time for the inspections will be required. Subsequent inspections may be conducted for either of two reasons:

- The preferred success path cannot be qualified at an acceptable ME level; other possible success paths may be considered.
- The need for additional information and inspection may become necessary during the seismic margin evaluation stage.

In the process of plant inspection, there is a need not only to identify seismically weak or possibly deficient areas but also to propose analyses, tests or actual alternative approaches to correct the deficiencies which may be individual or generic.

4.7 SEISMIC MARGIN EVALUATION

The objectives of the seismic margin review are specified in terms of performance criteria for structures, systems and components of the success path. Applicable codes and standards used in the design, material properties and data are used in the process. Criteria of performance include considerations such as: a) structural integrity and crack width to limit radioactivity release, b) loss or partial loss of function of unqualified elements, and process transients caused by unqualified system failures, must not cause damage to success path elements, c) maintenance of clear access to needed equipment and systems, d) maintained functionality and integrity of equipment and systems, e) limits on element displacements, etc.

The methodology for determining the withstand capability of various elements of the success path may include: a) comparison to similar elements that have been previously qualified; b) reference to successful performance from experience in earthquakes, and c) evaluation by analysis.

For the systems, structures and components that are not prescreened, a seismic evaluation for the ME is needed. The performance criteria should be adopted from available codes and standards with appropriate changes to utilize the conservatism inherent in the design. The sources of this conservatism are in load combination rules, response analysis parameters, and the inelastic behaviour and energy dissipation capabilities of the system. Attention should be paid to inherent margins especially as cracking and yielding occur with the resulting nonlinear behaviour. Mass coupling effects of equipment may also be significant.

4.7.1 Load Combinations

The load combinations used in the case of the ME are those that are likely to occur in combination with a seismic event. The load factor is taken to be unity. In principle, the normal operating loads are combined with the seismic load. The normal operating loads include: the dead load, the operating live load, the prestress load and the operating pressure loads. It is also possible to include pressure loads associated with postulated events as a consequence of the earthquake if any are assumed to occur.

4.7.2 Strength Criteria

The strength acceptance criteria for the margin review are based on existing codes and standards which include predictions of ultimate strength, stress, buckling capacity, etc. The current criteria are based on experience gained from the design and operation of existing plants. These criteria can be modified in the seismic margin evaluation to reflect the inelastic energy dissipation capacity of the system. If actual material properties are established by testing, these values would be used. If test values are not available, allowable stress in working stress design and factored resistance in limit state design values shall be used. Ultimate strength predictions by codes can be used in the strength calculations. Exceptions can be made if justifiable. An example is to take advantage of material strain hardening in calculating the ultimate load.

A well designed and constructed structure has higher actual seismic resistance than that calculated based on elastic analysis. Past yield nonlinear effects are mobilized to limit the imposed forces and increase the deformation. It is possible to conduct a nonlinear time history analysis and compare the maximum demand ductility to the ductility capacity.

An alternative means of accounting for the inelastic energy dissipation of structures and equipment at response levels beyond yield is the use of a ductility reduction factor. This factor is used to reduce the elastically calculated earthquake forces. The reduction factors may be calculated by assuming that the displacement of the elastic structure behaviour is the same as that when the structure behaves in a nonlinear manner. The advantage of this approach is that linear elastic analysis is still applicable while accounting for some of the inelastic energy absorption capability.

4.7.3 Structural Capacity

NPP structures are constructed of reinforced concrete, prestressed concrete, steel and masonry. The structural capacities of these materials are given by various applicable codes. Some structures, especially those with containment functions, are required to limit cracking to a small size such that the postulated radioactivity release remains limited. Although the strength and stability of the structure may be examined, it is important that the serviceability of in terms of deflection and function is assured.

4.7.4 Capacity of Components and Subsystems

The qualification of components and subsystems is by analysis and testing. The structural capacity is normally determined by analytical modelling. However, the functionality of components is normally demonstrated by testing. Equipment and subsystems that are not prescreened are required to be evaluated for seismic margin. The EPRI methodology proposes that equipment and subsystems be categorized into specific or generic categories according to their original qualifications and their treatment in the seismic margin review. Specific categories of components are to be individually evaluated. Examples of these components include reactor vessel and supports, steam generators and supports, primary coolant pumps and supports, primary coolant piping, electrical cabinet and control panel structures, sensors and diesel generator units. The demonstration of strength can mostly be done by analysis.

Electrical and control equipment is demonstrated to function during and following an earthquake by testing. In general, it is recommended that equipment be subjected to random frequency, multiaxis test input with a resulting test response spectrum that exceeds the required response spectrum in all frequency ranges. Function is normally

demonstrated by testing as it is much more difficult to demonstrate by analysis.
Some components and subsystems such as electrical raceways and HVAC ducting have no clear design codes. The qualifications of these systems are treated as special design cases. Most of these systems will be prescreened. If margin evaluation is conducted, it normally concentrates on supports and anchorage. In most of these systems, meaningful analysis and modelling is very difficult while testing is not practically feasible.

4.8 REQUIRED DOCUMENTATION

After conducting the seismic margin review study, a report should be prepared to document the procedures and results of the evaluation. The form of the documentation follows the steps of the study. In addition to the seismic margin review, the report may include some of the existing information that formed the background to the review. This section outlines the suggested format and content of the seismic margin report.

4.8.1 General

A general description of the plant site location, its geography, geology and brief description of the plant facilities and process equipment are required. The report should contain a description of unique systems and procedures including the backup systems for power supply, the shutdown system and any backup facility.

4.8.2 Seismic Design

This section should include information about the original seismic design basis for the plant structures and systems. The needed information should include identifying analytical methods, design criteria, seismic codes and standards, the input ground motion to structures and equipment (DBE and floor response spectra). The seismic analysis of structures, subsystems and their supports, mechanical and electrical equipment should also be reviewed.

4.8.3 The Review Team

The composition, qualification and experience of all members of the review team should be included. In addition, the qualification and the expertise of consultants and support staff should be documented.

4.8.4 Selection of the Margin Earthquake

The procedure used in the selection of the ME should be reviewed. Seismo-tectonic evaluations, special seismicity studies and site specific evaluations should be included.

4.8.5 Performance Criteria

The criteria of performance or acceptance for each element and system of the success path should be stated. The performance criteria needed for the margin study under the ME conditions are different from those used for design under DBE conditions.

4.8.6 Margin Evaluation Basis

The procedures for calculating the structural loads and the failure criteria are detailed. This section should include discussions whether the response of the structure was scaled or a new seismic analysis was performed. A review is required to indicate whether existing models or new models were used. The reported results should include response parameters such as displacement, velocity, accelerations, storey shears and moments. The discussion should review load combinations and floor response spectra details.

4.8.7 Safety Margin Evaluation

This section represents the core of the report. It should contain details of the overall approach taken, the screening criteria, description of the identified preferred and alternate success paths and all structures and equipment. The preparation for the field inspection is provided with a discussion of the prescreening process for the structures and equipment. The numbers and purposes of the visual inspections are to be described, including the inspection to select and confirm the preferred and alternate success paths, the one to prescreen systems and components and any additional inspections that were conducted.

4.8.8 Elements Qualified by Analysis or Test

Components that are not screened out should be qualified to the ME level by analysis, test or comparison with tested components or components which have experienced a strong motion earthquake. This section should identify systems and equipment, seismic margin criteria, typical analysis and the results. Discussions are to be made of the analysis methodologies, scaling methods, criteria for acceptable performance and proposed modifications to the components to meet the criteria.

4.8.9 Summary and Conclusions

The review of the success paths should lead to statements concerning the qualification of the success path components to the ME level. Any component that does not meet the criteria is identified with proposed modification and upgrade requirements.

5. CONCLUSIONS AND RECOMMENDATIONS

A study was conducted to recommend a methodology for assessing the seismic withstand capacity of existing CANDU NPPs in Canada such as the Pickering A NGS. The proposed methodology is derived and adapted from the EPRI methodology for the seismic margin assessment of nuclear power plants with some modifications. An implementation plan for the application of the proposed methodology for the Pickering A NGS was discussed. On the basis of the review and analysis presented in this study, the following conclusions and recommendations are made:

5.1 CONCLUSIONS

a) Of the available seismic margin review methodologies, the EPRI approach, with appropriate modifications, is judged to be the most suitable for application to the seismic margin review in Canada.

b) The proposed methodology for the seismic margin review is an adaptation of the EPRI approach. The proposed approach is rational and defensible as compared to other existing methodologies. Modifications are made to the EPRI methodology in areas such as: the definition of the margin earthquake; composition of the review team; systems and elements in the likely success path; the human factor; and some of the proposed IPEEE policy upgrades including relay chatter, liquefaction and the internal and external consequences of the seismic event such as loss of off site power.

c) The proposed seismic margin review methodology can be implemented in the following steps:
   - selection of the review team
   - determination of the ME and its definition
   - definition of performance criteria
   - determination of the preferred success path and alternate path(s)
   - prescreening by evaluations and visual inspections
   - conducting the qualifications and seismic margin review work
   - documentation.

d) The margin earthquake is to be determined on the basis of seismo-tectonic, regional geological and local site conditions. The existing strong motion database can be used to generate the time histories associated with events at or near the site or at sites that are seismologically similar to the plant site.

e) The adopted performance criteria for a possible preferred success path and an alternative path for the Pickering A NGS includes the structures, systems and components involved in the following functions:
   - safe shutdown of the reactor and maintaining it in a shutdown condition.
   - maintenance of the fuel cooling by the primary cooling system - or alternatively by the emergency coolant injection system in case of loss of coolant accident assumption.
   - containment of postulated radioactive releases.
   - monitoring and control of critical and safety functions

f) It is important to point out that the seismic margin review process provides the state of the art evaluation of the NPP's seismic withstand capacity. However, it is not a guarantee of performance during a major seismic event. Research work is being conducted to introduce some of the following aspects in the margin review methodologies:
   - consequences of human performance under the stressful conditions of a major seismic event.
   - the effects of wear, tear and aging on the performance and functions of equipment and systems. Qualification of equipment by testing is performed on mostly new components. However, experience data is applicable to old equipment to a certain extent.
   - small hydraulic systems associated with sensors and pneumatic systems may be vulnerable in a major seismic event. Special effort is needed in the qualification of these systems.
   - there remain a few sources of unquantified hazard. Some of these hazards include operational effects such as wear, chemical reactions, change of material behaviour and characteristics with time and the effect of design and construction shortcomings on the performance of systems and components.

5.2 RECOMMENDATIONS

a) It is recommended that the proposed methodology for the seismic margin review be adopted. The methodology is an adaptation of the EPRI approach to suit the specific conditions of the Canadian CANDU NPP such as the Pickering A NGS.

b) It is recommended that a seismological study be conducted to determine the site specific characteristics of the margin earthquake at the Pickering A site. The recommended approach for the seismological study is based on the seismo-tectonic, local geological and site specific conditions. The results from the seismological study should be correlated with available studies in neighbouring US locations. The recommended seismological study should be subjected to peer review in order to maximize the confidence in the results.

c) It is recommended to conduct a study to specify the review objectives of various elements and systems and to define performance and capacity criteria of structures and components. Detailed performance, ultimate capacity and strength criteria need to be identified for various elements.

d) It is recommended that care should be exercised when applying some of the available foreign fragility data and HCLPF capabilities of elements to a CANDU NGS. The available information and database may not be readily applicable to all situations given that anchor and construction methods in different NPPs, for example, are different and may result in different earthquake withstand capacities.

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